PART FIVE

THE REFERENCE EVENT METHOD OF SEISMIC LOCATION FOR MINE RESCUE SYSTEMS

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I. SUMMARY

The location of trapped miners from their seismic signals will be inaccurate if we assume the P-wave propagation velocity is a constant. P-wave velocities are anything but constant in regions about mines, so some calibration is necessary to obtain more accurate seismic locations.
The reference event method compares the time arrivals of signals generated by the miners with those previously recorded from a reference or calibration event in the vicinity of the miners. This method locates the miners' position relative to the calibration source. Hence, the location of the miners is absolute if the reference event position is known absolutely, usually from surveys and mine maps.

Advantages resulting from the system, besides greater accuracy, are locations independent of the velocity model assumed, the same solution from the full array and from any subset of four or more seismometers in the array (three if the miners' depth is known), fewer seismometers required, and no complex computers required for analysis.

VELA Uniform experience shows that the accuracy of locations of teleseismic explosions and earthquakes is improved by an order of magnitude over locations computed from average travel time curves.

Each calibration event is applicable only over a limited range. We recommend a field test of the method at a mine to measure its location accuracy, the range of effectiveness for each calibration event, the number of seismometers needed, and the number of reference events required per mine.

From these experiments we could decide whether the reference event method was useful and, if so, what form a practical rescue system would take.

II. INTRODUCTION

To date the seismic location system for locating miners trapped underground has been applied assuming a uniform isotropic earth. The use of this assumption leads to errors of one to several hundred feet in the seismic locations (Westinghouse 1972).* Under favorable conditions we should expect time reading errors on the order of one tenth of a cycle of the dominant signal period. With the 80 Hz to 100 Hz signals, the 1 to 2 millisecond time reading errors could account for mislocations on the order of 10 to 20 feet, assuming no errors in the earth model. Thus the errors experienced by Westinghouse can only be accounted for by the inappropriate velocity model of the geologic region around the mine.

If seismic locations to within less than a few hundred feet are to be attained, then one of two approaches must be followed. Either the geologic structure defining the velocity about the mine must be determined by a refraction survey or some other means, or reference events must be used to calibrate the P-wave travel times to pre-set seismometer locations. The purpose of this work is to develop the reference event theory and discuss its application for the mine rescue systems; refraction surveys and more sophisticated velocity models are discussed elsewhere in this report.

III. THEORY

The concept of the relative event approach is fairly simple. Since accounting for the variations in the velocity of propagation is necessary for accurate seismic locations, why not measure the signal delays from source to seismometers directly with a test event? Repeated sources from the same location will reproduce the same propagation delays. Moreover, sources only slightly displaced from the reference event location will nearly reproduce the same propagation delays. To compute the change in location of the new (unknown) event from that of the reference event, we can use any velocity model we wish since most of the path (and hence, most of the propagation delay) from source to seismometer almost duplicates that from the reference event. Thus by computing the small displacement accurately from the known test event, we can determine accurately the location of the unknown event.

* Westinghouse Contract H0210063 with Bureau of Mines.

In earthquake seismology the standard location method (Geiger 1910) minimizes the sum of the squares of the residuals between measured P-wave arrivals, t_i, and the calculated arrivals, F_i, based upon some velocity model

$$t_i - F_i(u) = e_i \qquad i = 1,2, \ldots , \quad . \quad n. \tag{1*}$$

The calculated time, F_i, for a P-wave to travel from some particular event to the $i^{\underline{th}}$ seismometer is a function of the event coordinates, u, (actually $u_1 = x_o$, $u_2 = y_o$, $u_3 = z_o$, and $u_4 = t_o$) and the $i^{\underline{th}}$ seismometer coordinates x_i, y_i, z_i, as well as well as the P-wave velocity between the two.

$$F_i(u) = F_i \quad (x_o, y_o, z_o, t_o / x_i, y_i, z_i) \tag{2}$$

F_i is a non-linear function of the space and time coordinates of the seismometers and events. This is true even if the velocity is assumed to be uniform. Hence, the equations are easier to solve in a least squares sense if we expand F_i in a Taylor's series and neglect the higher order terms.

$$F(u) = F(u^*) + \frac{\partial F}{\partial u_1}(u_1 - u_1^*) + \frac{\partial F}{\partial u_2}(u_2 - u_2^*) + \frac{\partial F}{\partial u_3}(u_3 - u_3^*) + \frac{\partial F}{\partial u_4}(u_4 - u_4^*) + \ldots.. \tag{3}$$

The approximation is good when the new location, u, is in the vicinity of u* for which F(u*) is presumably known.

Now the equation (1) can be written as

$$\sum_{k=1}^{4} \frac{\partial F_i}{\partial u_k} (u_k - u_k^*) = t_i - F_i(u^*) = R_i \tag{4}$$

* References to Figures, Tables, and Equations apply to those in this Part unless otherwise noted.

or in matrix form

$$B \, \delta = R \tag{5}$$

where B is the condition matrix

$$B = \begin{vmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \frac{\delta F_i}{\delta u_1} & \frac{\delta F_i}{\delta u_2} & \frac{\delta F_i}{\delta u_3} & \frac{\delta F_i}{\delta u_4} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{vmatrix} \tag{6}$$

δ is the displacement vector between a new (u), and our original (u*) source position.

$$\delta = \begin{vmatrix} u_1 - u_1^* \\ u_2 - u_2^* \\ u_3 - u_3^* \\ u_4 - u_4^* \end{vmatrix} \tag{7}$$

and R is the vector of residuals between the calculated and measured time arrivals, $t_i - F_i^* = e_i$.

The least squares solution of these equations is

$$\delta = (B'B)^{-1} B' R . \tag{8}$$

For the development of the method and its associated errors see Flinn (1965).

To apply the Geiger method we merely have to choose coordinates of an arbitrary event location, $u^* = (x_o^*, y_o^*, z_o^*, t_o^*)$, and perform the matrix multiplication iteratively until the solved-for-displacement vector, δ, goes to zero.

In the usual case the least squares solution still leaves us with residuals ($\Sigma_i \ R^2_i$) which are too large. Moreover the resulting location estimates from any of the n-1 or n-2 subsets of the seismometer network can be quite different than the location estimate of the full n-seismometer network. Consequently, weak sources and strong sources with identical locations are apt to be located apart from each other.

The situation is quite different if the first location estimate, ($u^* = x_o^*, y_o^*, z_o^*, t_o^*$) is from a calibration source in the vicinity of the unknown. In this case several advantages result:

1. The least square residuals are small.

2. The accuracy of the method is relatively independent of the velocity model we assume in the vicinity of the source.

3. Any subset of four or more seismometers in the network give a location as accurate as the full network. As a result weak event locations are frequently as accurate as those of strong events.

4. Fewer seismometers are needed in the network to yield accurate locations.

5. The waveforms at a particular seismometer from the calibration event and the unknown event often are quite similar to each other. Thus relative timing between the events is much easier since it is not limited to first motions but can make use of large dominant features later in the P-wave train.

6. Utilizing the reference event method a computer can identify which of n seismometers have had reading errors and by how much, as long as no more than a third of the seismometer readings are in error.

IV. VELA UNIFORM EXPERIENCE

For several years the VELA Uniform program has made use of the reference event method for locating teleseismic earthquakes and underground explosions. In a study using various networks from 4 to 13 stations, Chiburis 1968, compared the accuracy of teleseismic locations both with and without travel time corrections for 17 underground explosions at the Nevada Test Site. The stations ranged from 2000 to 9000 kilometers from the epicenter. Chiburis compared both the travel time residuals, which is the method we have described in the previous section, and travel time anomalies, which calibrates the difference in arrival times between pairs of seismometers using reference events. The accuracies of the travel time anomaly method and the travel time residual method are essentially the same. There are operational advantages to travel time anomalies, since the method is independent of the time origin of either the reference event or unknown event.

Figure 1 shows the location error in kilometers for 17 NTS explosions versus the number of recording stations both with and without travel time corrections. These results imply that the location accuracy is independent of the number of stations.

Figure 2 shows the location errors for NTS explosions versus the azimuth of the network. The network azimuth is measured as the widest angle drawn from the epicenter to all pairs of stations. Location accuracy improves as network azimuth increases both with and without travel time corrections. Similar data for Asian explosions and earthquakes in Figure 3 show the same trends. These experiments show that the reference event method improves locations by an order of magnitude over the uncalibrated least squares locations.

We can make an estimate of the ultimate accuracy attainable for relative locations of teleseismic earthquakes from the spectral considerations. For wide-aperture networks the timing accuracies of signal arrivals are approximately 0.1 second with the signal spectra peaked near 1.0 Hz.

From the timing error and velocity we have

$dt = 0.1$ seconds, expected timing inaccuracy.

$v = 15$ km/sec, apparent (average) P-wave velocity at earth's surface.

$du = v \; dt = 1.5$ km, expected location error.

Thus the 1-to 2-kilometer relative location accuracy achieved by the wide-aperture VELA networks as indicated in Figure 3 approaches the asymptotic limit of location accuracy we can expect.

V. FIELD METHODS FOR MINE RESCUE

We consider here three ways in which the influence of the earth may be accounted for in computing the location of trapped miners seismically: 1) the uniform velocity approach; 2) the refraction survey approach; and 3) the reference event approach. Each method may be applicable in different circumstances.

The first approach involves little sophistication in attempting to improve the seismic location accuracy. Upon detecting seismic signals from trapped miners, the approximate location of their source is computed assuming a uniform, isotropic earth. Then if the seismic array does not surround the

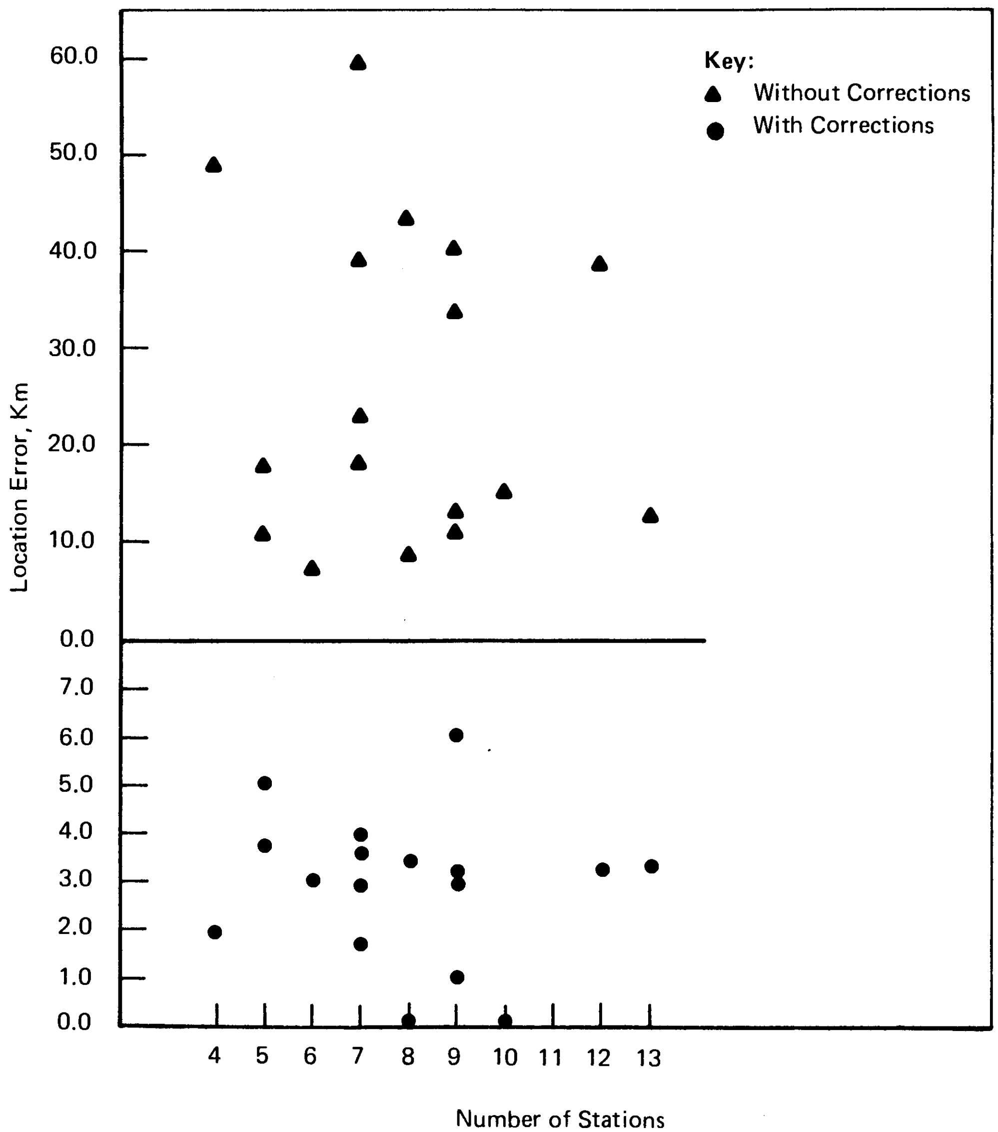

FIGURE 1 LOCATION ERROR VERSUS NUMBER OF RECORDING STATIONS

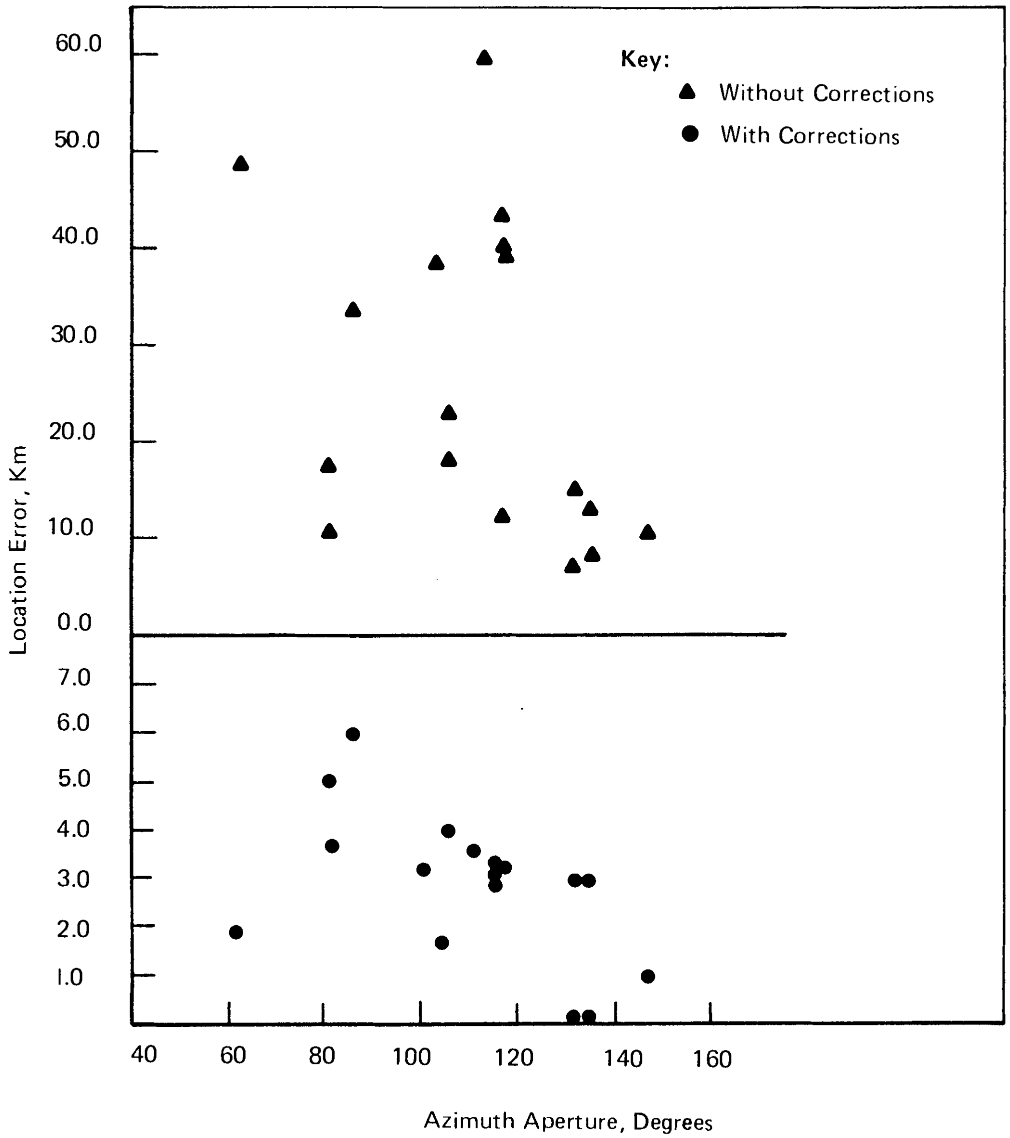

FIGURE 2 LOCATION ERROR VERSUS AZIMUTH APERTURE

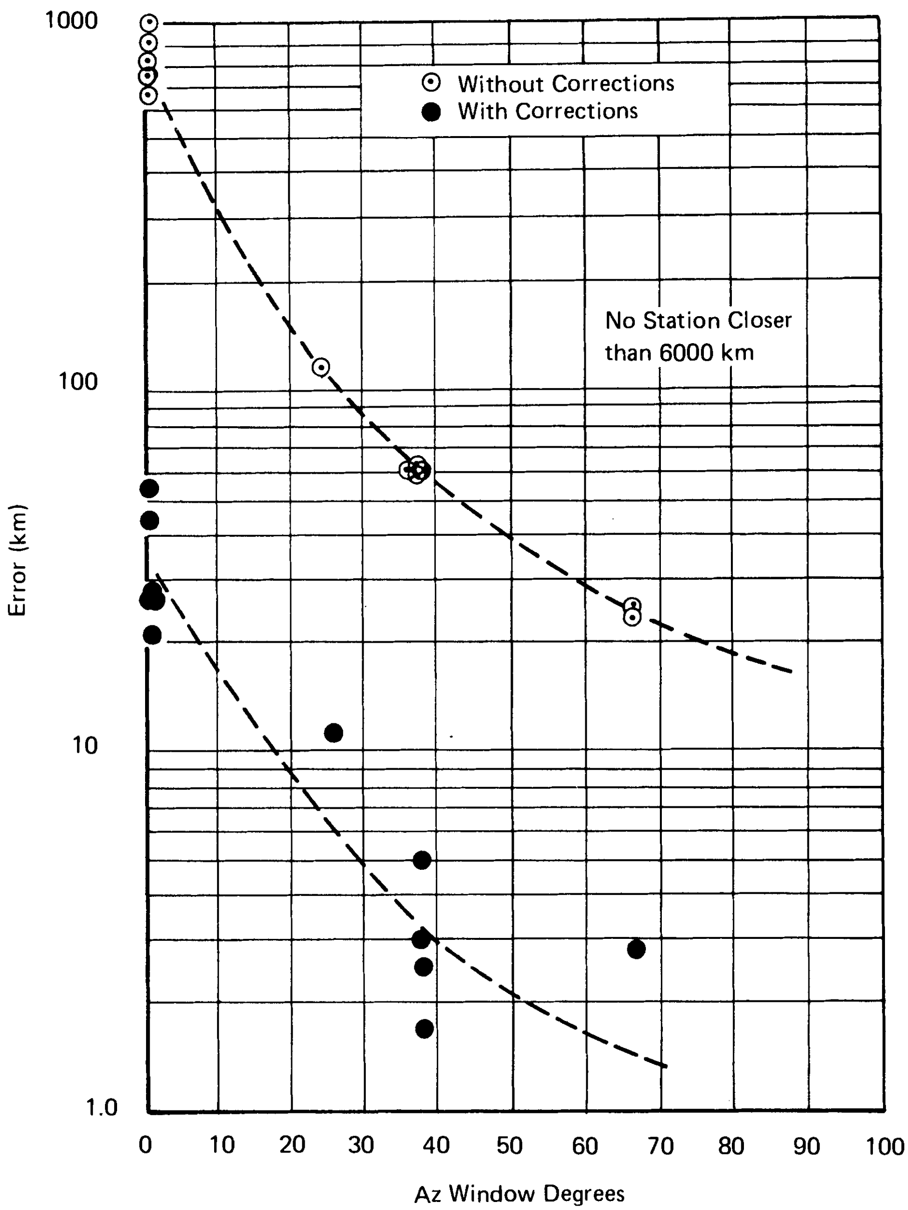

FIGURE 3 LOCATION ERROR VERSUS NETWORK AZIMUTH APERTURE

miners' position, or if the dimensions of the seismic array are too large, the seismometers may be redeployed in a smaller array surrounding the miners. Subsequent signals from the miners may then provide a more accurate location estimate. However, we would not place any confidence in the seismic location for positioning a drilling rig for a life-support hole. Rather the drilling rig location would be based only upon mine maps and companion surveys on the surface of the ground. Seismic locations would indicate approximate locations of trapped miners. In this way seismic location errors as large as 200 feet or more may be acceptable.

Advantages of this approach are that it is simple and that it requires no precalibration of the mine.

Disadvantages of this approach are that rescue operations may have to depend upon a more accurate seismic location and that there may not be time nor subsequent signals from the trapped miners to make redeployment of the seismometers practical.

The second approach is to calibrate the geology surrounding the mine with a refraction survey. Then the uniform isotropic earth assumption is discarded for a more realistic model. Powell (1972) illustrated the magnitude of location errors arising when a uniform velocity was used instead of the true structure in a few three-layer models. In optimum cases we may improve the location accuracy by an order of magnitude, but perhaps somewhat less in practice. The reason is that, although the refraction survey may describe the first order variations in the seismic velocities about the mine, it may not be detailed enough to measure the secondary features (velocity anomalies, faults, fractures, etc.) in the vicinity of the seismometers. These secondary variations in geology may cause the test array of seismometers to behave differently than the array deployed in an emergency.

There are trade-offs to be considered in this situation, in terms of the complexity of the velocity model envisaged and the extent and analysis of the refraction survey required. The size of the uncertainties remaining in coal mining environments will have to be resolved by experiment. If the refraction survey is carried out at the mine following a disaster rather than in a pre-calibration exercise, the importance of having trained, experienced personnel to perform it cannot be underestimated. For the interpretation of the data, they will require at least a general knowledge of the geological structure of the region. In principle, it is also possible to improve the location accuracy by iterating the velocity model as a result of a preliminary location; the improvements obtainable with this approach remain to be determined.

Advantages of approaches relying on calibrated geology are that a reduction of the expected seismic location errors by factors of 2 to 5 may provide sufficient accuracy for positioning a drilling rig in the most favorable circumstances or at least allow a miner to be located to within a dimension of a pillar. However, several actual or potential disadvantages still remain. The locations may still be inaccurate but the inaccuracies unknown. The proper velocity model may be applied inaccurately, perhaps due to the lack of trained personnel, during an actual emergency. Finally, the emplacement of seismometers during the refraction survey may be sufficiently different from those used during the location procedure, that the velocity model may not apply well enough to the location array.

The third approach is the reference event method which requires a seismic array permanently installed (or seismometer positions chosen in advance of disasters) and pre-di·aster calibration of the mine with seismic signals from different parts of the mine.

Advantages of this approach include improved location accuracy by at least an order of magnitude over uniform velocity models, elimination of the need of refraction surveys, and no fancy data processing techniques.

Disadvantages of the method include the need for precalibration of the mine, permanently installed seismometers (or permanently assigned seismometer locations), and perhaps more calibration signals than we might wish, especially as the mine dimensions increase.

The density of calibration signals required, the number and placement of seismometers, and the costs of the method are questions to be resolved by experiment.

Several designs of the seismic location system utilizing the reference event approach are possible. One is to install seismometers, cables and recording instruments permanently around the mine. Fire drills (test seismic signals) are taken periodically from different parts of the mine as the mine dimensions expand. These recordings, clearly labeled as to source location, can be reproduced on clear plastic overlays for easy comparison with signals recorded during an emergency. In this way good seismometer locations would be assured (buried for improved signal-to-noise ratio) and the equipment would demonstrate its reliability as calibration (reference) events were recorded about the mine. Signals could be read and approximate locations determined by analysts without the need for a computer. With or without a computer, mine personnel could acquire training in operating the system as calibration data were collected.

A second design would be to locate test seismic sources (small explosives or weight drops) throughout the mine which can be triggered from the surface. When a seismometer array has been deployed during an emergency, and an approximate location of trapped miners determined from their signals assuming a uniform velocity model, then test seismic sources would be set off in that section of the mine. The signals from the miners and those from several test sources would be compared. Then the relative location of the trapped miners would be determined from the test signals which most closely matched those generated by the miners.

The characteristics of the three types of systems, utilizing the uniform velocity, the refraction survey, and the reference event methods, are summarized in Table 1.

VI. FIELD EXPERIMENT

The reference event method should be tested by a controlled experiment at a mine. The Westinghouse data taken to date do not provide data from a multitude of close to widely spaced sources received by a fixed seismometer array. The objectives of such an experiment will be (1) to demonstrate whether the relative event method, which has been so successful for locating teleseismic earthquakes, can also be applied to seismic sources in mines, and (2) to determine the calibration range of applicability of the reference events.

The field experiment should comprise from 10 to 15 well-placed seismometers. These sensors should be buried below the weathering layer in drill holes if necessary. Every effort should be made to attain good signal sensitivity on single sensors so array summations are not necessary. Different

TABLE 1

SEISMIC LOCATION METHODS

1. Uniform Velocity Method

Features:	Installation	- after disaster is reported
	Precalibration	- none
	Location Accuracy	- several hundred feet
	Drill Locations By	- mine maps for precise placement, seismic locations indicate section of mine.

Advantages:
Simple
No precalibration
No capital outlay prior to disaster
Minimum training of mine personnel required

Disadvantages:
Seismic locations can indicate only general area of miner
Deployment of extra seismometers after first signals detected may be desirable

2. Refraction Survey Method

Features:	Installation	- after disaster is reported
	Calibration	- refraction survey to model velocity structure around mine
	Location Accuracy	- will vary on complexity of geology and thoroughness of refraction survey; probably to within 100 feet
	Drill Location By	- mine maps for precise placement, seismic locations narrow search.

Advantages:
More accurate locations than uniform velocity model

Disadvantages:
Location accuracy may be unknown
Velocity model may be incorrectly applied in an emergency
Calibration required

3. Reference Event Method

Features:	Installation	- predisaster; permanent
	Precalibration	- tests made throughout mine as mine dimensions expand
	Location Accuracy	- 10 to 50 feet with high confidence
	Drill Locations By	- mine maps and seismic locations jointly

TABLE 1 - Continued

3. Reference Event Method - Continued

Advantages:	Accurate locations No refraction surveys required Data processing required fairly simple System in place when emergency arises Mine personnel familiar with system from mine Calibration tests
Disadvantages:	Predisaster mine installation, tests, and costs Necessary system tests required as mine dimensions expand Some mine personnel must be trained on system

types of sources should be used (e.g., timber on mine floor, sledge on roof bolts) at each source location so the method can be demonstrated with reference and unknown events of the same and different types. Minimum source displacements may be on the order of 25 to 50 feet. Maximum source displacements should be 1000 feet or more if possible. Different sections of the mine should be tested including ones for which the seismometer array surrounds the event location (360° aperture) and ones for smaller apertures. One value of having a sufficient number of seismometers is that partial arrays (but more than 3 or 4 sensors) with varying apertures can be compared with the full array.

Costs of running seismic exploration crews within the United States average between $30,000 and $50,000 per month including costs for dynamite and drilling shot holes. Although we propose to use 10 to 15 sensors all in bore holes, the holes will not be deep (average depth 50 feet) so drilling costs for the mine tests should not exceed those of a normal exploration crew. The cables, sensors, and instruments required would be available or easily obtainable by an exploration crew. Hence, a geophysical service company should be able to conduct a field test of the relative event method for $1,000 to $2,000 per day and complete it within two to four weeks.

As a result of this experiment we should be able to indicate:

1) whether the reference event method works in mines,
2) over what range a reference event is applicable,
3) the source location accuracy of the method,
4) the number of reference events needed per mine,
5) the minimum number and placement of sensors required in a workable field system,
6) the analysis procedures to be followed, and
7) an estimate of the capital and operational (emergency, calibration, and testing) costs in a practical field system.

VII. CONCLUSIONS

1. We have considered two alternative seismic approaches to improve the accuracy of seismic locations for miners trapped underground over methods which assume a uniform P-wave velocity in the earth. The first approach uses seismic measurements, such as a refraction survey, to calibrate the velocity

structure about the mine. The second approach calibrates the source-to-seismometer travel paths with reference events at known locations in the mine.

2. The method yielding the most accurate seismic locations is the reference event method. When the displacement between the unknown and reference events is small, the location accuracy will be limited only by the timing accuracy of the signals.

3. The reference event method provides absolute rather than merely relative location accuracy since calibrations are tied to surveyed (non-seismic) locations. Methods based upon purely seismic measurements may provide accurate relative locations (small least squares error) but still contain absolute biases (lateral shifts between true and calculated locations).

4. The reference event method has the disadvantages of requiring calibration events, permanently installed seismometers or prelocated calibration sources triggered from above ground, and several reference events per mine for complete calibration.

5. A field installation utilizing the method has several operational advantages. As well as accuracy, these include readiness in the event of a disaster, fire-drill testing of the system by calibration events, familiarity with the system on the part of mine personnel, and no complex computers or analysis required.

6. We recommend field tests to verify the method. Key questions to be answered include the range of effectiveness of each reference event and the number of reference events required to completely calibrate a mine.

7. A field test could be conducted at a mine over a period of two to four weeks for costs not exceeding those incurred by Westinghouse in previous seismic experiments at a mine. Total costs should be in the $25,000 to $50,000 range, or less.

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